An Optical Precursor to the Recent X-ray Outburst of the Black Hole Binary GRO J1655-40

Jerome A. Orosz[1]
Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802-6305
orosz@astro.psu.edu

Ronald A. Remillard[1]
Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139-4307
rr@space.mit.edu

Charles D. Bailyn[2]
Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101
bailyn@astro.yale.edu

and

Jeffrey E. McClintock
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
jem@cfa.harvard.edu

ABSTRACT

The All Sky Monitor on the *Rossi X-ray Timing Explorer* detected an X-ray (2-12 keV) outburst from the black hole binary GRO J1655-40 beginning near April 25, 1996. Optical photometry obtained April 20-24, 1996 shows a steady brightening of the source in B, V, R, and I beginning about six days before the start of the X-ray outburst. The onset of the optical brightening was earliest in I and latest in B. However, the rate of the optical brightening was fastest in B and slowest in I. The order of the increases in the different optical filters suggests that the event was an "outside-in" disturbance of the accretion disk. The substantial delay between the optical rise and the rise of the X-rays may provide indirect support for the advection-dominated accretion flow model of the inner regions of the accretion disk.

Subject headings: binaries: spectroscopic — black hole physics — X-rays: stars — stars: individual (GRO J1655-40)

[1]Visiting Astronomer at Cerro Tololo Inter-American Observatory (CTIO), which is operated by the Association of Universities for Research in Astronomy Inc., under contract with the National Science Foundation.

[2]National Young Investigator

1. Introduction

GRO J1655-40 was discovered July 27, 1994 with the Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma Ray Observatory* (Zhang et al. 1994). Unlike most "X-ray novae," GRO J1655-40 continued to have major outburst events in hard X-rays long after its initial high-energy outburst (see Harmon et al. 1995a). There was an outburst event in late March 1995 (Wilson et al. 1995) and another one starting in late July 1995 (Harmon et al. 1995b). The relatively short recurrence times between the X-ray outbursts may be due to the relatively large value of the average mass transfer rate [$\dot{M}_2 = 3.4 \times 10^{-9}\, M_\odot$ yr^{-1}, see Orosz & Bailyn 1997 (hereafter OB97)]. After the July/August 1995 hard X-ray outburst, the source apparently settled into true X-ray quiescence. From the period of late August 1995 to April 1996, the source was not detected by BATSE (Robinson et al. 1996). The *ASCA* X-ray observatory made several pointed observations in late March 1996 and found the X-ray luminosity (2-10 keV) of the source to be quite low: $L_x \approx 2 \times 10^{32}$ ergs s^{-1} (see Robinson et al. 1996, Y. Ueda private communication). This extended period of X-ray quiescence ended in late April 1996 when the all sky monitor (ASM) on the *Rossi X-ray Timing Explorer* (*RXTE*) satellite detected an increase in the 2 to 12 keV X-ray flux (Remillard et al. 1996; Levine et al. 1996). The source was again detected by BATSE starting in late May 1996 (Harmon et al. 1996). GRO J1655-40 has remained a persistent X-ray source for several months after the April outburst, unlike the case in 1994-1995 where there were several shorter outburst events.

From optical observations made during late April and early May, 1995 Bailyn et al. (1995) established the spectroscopic period ($2\overset{\text{d}}{.}601 \pm 0\overset{\text{d}}{.}027$) and the mass function ($3.16 \pm 0.15\, M_\odot$) of the system, thereby establishing GRO J1655-40 as one of the latest members of the class of objects often referred to as "black hole X-ray transients." The B, V, R, and I light curves obtained February and March 1996 (during the X-ray quiescence) by OB97 were dominated by ellipsoidal variations from the secondary star. The grazing eclipse of the accretion disk by the star allowed OB97 to model the March 1996 light curves to find precise values of the orbital inclination ($i = 69.5 \pm 0.08$ deg) and the mass ratio ($Q = 2.99 \pm 0.08$). The model fits to all four filters were excellent—the standard deviations of the residuals were less than 0.02 magnitudes. Furthermore, the V and I light curves showed no noticeable change between February 1996 and March 1996, indicating that GRO J1655-40 probably had reached its minimum overall brightness level. Here we report additional photometry of GRO J1655-40 obtained late April 1996, starting fortuitously close to the onset of the X-ray outburst. Using the March 1996 light curves to establish a "quiescent" brightness level for each filter, we demonstrate below that the April photometry shows clear evidence for an optical brightening well *before* the brightening in the X-rays occurred. We discuss below the optical and X-ray observations and reductions, the April 1996 optical light curves and the optical precursor, and the possible implications these observations have for various models of the outburst cycles and quiescent systems.

2. Observations and Reductions

2.1. Optical Observations

Photometry of the source was obtained April 20-24, 1996 with the CTIO 0.9 meter telescope, the Tek 2048×2046 #3 CCD, and standard B, V, R, and I filters. The night of April 20 was photometric and we observed a total of 59 Landolt (1992) stars in five different fields, using the standard filters. IRAF tasks were used to process the images to remove the electronic bias and to perform the flat-field corrections. The programs DAOPHOT IIe and DAOMASTER (Stetson 1987; Stetson, Davis, & Crabtree 1991; Stetson 1992a,b) were used to compute the photometric time series of GRO J1655-40 and several field comparison stars. The differences between the calibrated magnitudes of nine stable field stars and their mean DAOPHOT instrumental magnitudes were computed and the averaged differences were used to correct the rest of the stars' instrumental magnitudes to the standard system. The uncertainty of the transformations between the DAOPHOT instrumental magnitudes and the calibrated magnitudes are 0.056 mag in B, 0.006 mag in V, 0.006 mag in R, and 0.009 mag in I. Note that these errors reflect the uncertainty in the zero points of the magnitude scales—the internal errors of the instrumental magnitudes within each filter are much smaller. The relatively large error of the B transformation is because the color term in B is about ten times larger than the other three color terms, resulting in more scatter in the differences between the standard B magnitudes and the instrumental B magnitudes. We find that the pho-

Table 1
Fitted Parameters for the April Light Curve Residuals

filter	slope (mag/day)	coefficient of correlation	fitted time of initial rise (HJD 2,449,000+)	(UT day in 1996)
I	-0.0423 ± 0.0019	-0.96	1192.76 ± 0.29	April 19.25 ± 0.29
R	-0.0453 ± 0.0018	-0.97	1192.88 ± 0.26	April 19.37 ± 0.26
V	-0.0553 ± 0.0012	-0.99	1193.32 ± 0.15	April 19.82 ± 0.15
B	-0.0759 ± 0.0020	-0.99	1193.84 ± 0.18	April 20.34 ± 0.18
X-ray[a]	20.44 ± 1.09[b]	$+0.97$	1198.88 ± 0.78	April 25.38 ± 0.78

[a]Determined from a fit to 23 points between HJD 2,450,199.09 and HJD 2,450,203.18.

[b]The units are counts per second per day.

Note.—All errors shown are 1σ.

tometric calibrations from the March and April data sets are the same to 0.005 magnitudes.

2.2. X-ray Observations

A recent paper by Levine et al. (1996) describes the ASM instrument on the *RXTE* and the data analysis procedures. The ASM has been operating more or less continuously since February 21, 1996, providing roughly 5 to 10 scans of a given source per day. GRO J1655-40 was not detected above the level of ≈ 12 mCrab before April 25, 1996 (Remillard et al. 1996; Levine et al. 1996). After that, the intensities derived from daily averages of the measurements were 71 ± 15 mCrab on April 25, 420 ± 30 mCrab on April 26, 586 ± 15 mCrab on April 27, 802 ± 9 mCrab on April 28, and 1077 ± 30 mCrab on April 29 (e.g. Remillard et al. 1996). The X-ray light curve of GRO J1655-40 is given in Levine et al. (1996). We obtained the X-ray data from the public archive maintained by the *RXTE* Guest Observer Facility.

3. Optical Light Curves and the Optical Precursor

The eclipsing light curve code used to model the March 1996 photometry is described in some detail by OB97. Briefly, the code uses full Roche geometry to account for the distorted secondary star. Light from a circular accretion disk and the effects of mutual eclipses are also accounted for. The code computes the observed flux as a function of the orbital phase, so the $BVRI$ light curves from March 1996 were each "folded" using the spectroscopic ephemeris given in OB97 and fitted simultaneously. The best fitting model consists of four different curves giving the B, V, R, and I magnitudes as a function of the photometric phase. These four curves were "unfolded" using the spectroscopic ephemeris, yielding model curves which give the magnitude as a function of time.

The orbital phase during our April observations is determined precisely (to within 0.008 of an orbital cycle) by the spectroscopic ephemeris given in OB97. Similarly, the shapes and amplitudes of the model light curves for the quiescent state, which are shown in Figure 1, are precisely specified in OB97. Figure 1 shows the April photometry plotted with these model curves. There is a clear systematic deviation of the observations from the model in all four filters. Figure 2 shows the residuals in the sense of the April data *minus* the March model (propagated forward in time to April). The systematic deviation from the model in all four filters is now quite clear: the source increased in brightness starting near April 20. In each case, the residuals on a magnitude scale decrease linearly with time (see Table 1 for the parameters of the linear fits to the residuals). An inspection of Figure

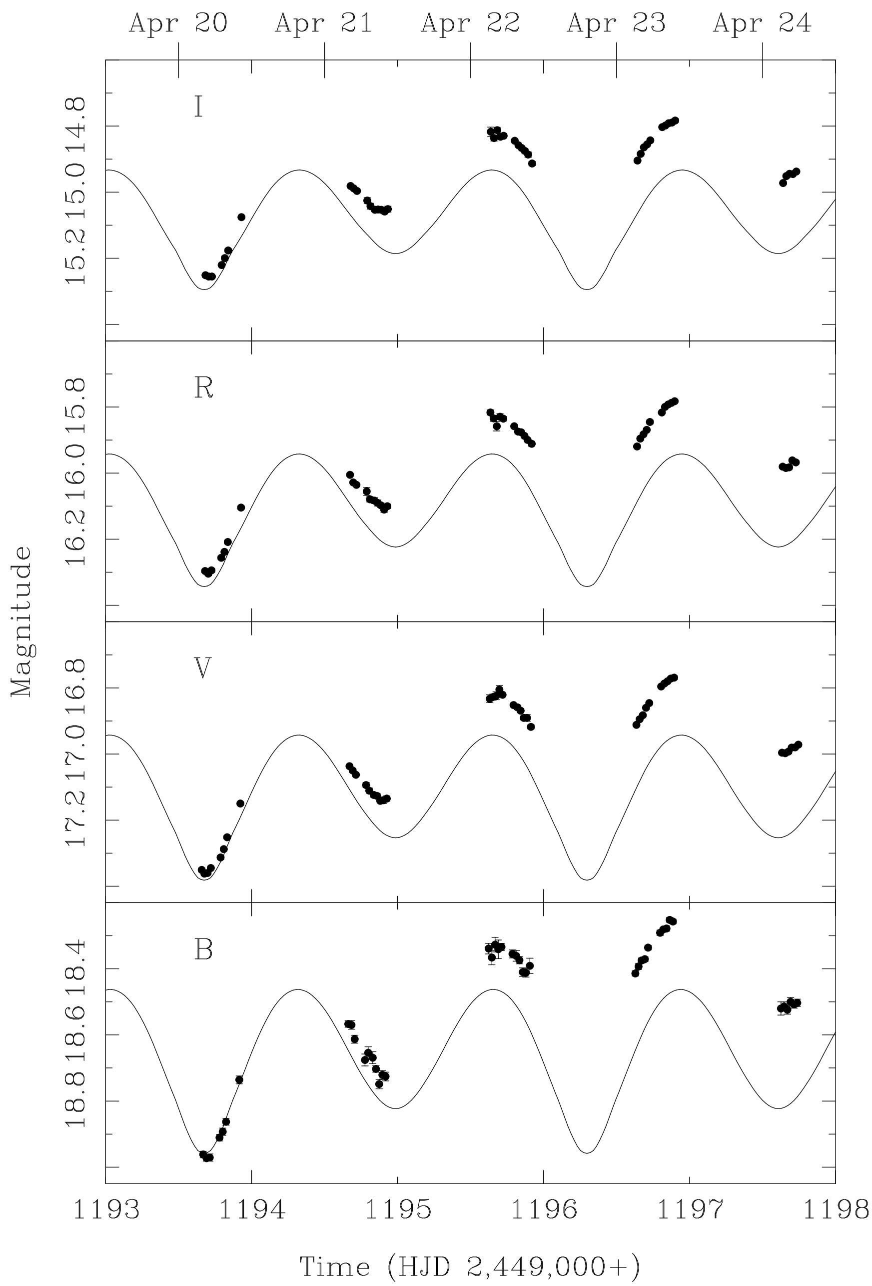

Fig. 1.— The observed light curves of GRO J1655-40 from April 20-24, 1996 (points) and the models which fit the light curves from March 18-25, 1996 (solid lines). The same magnitude range (0.85 mag) is shown for all four panels, demonstrating the notable decrease in the light curve amplitudes from B to I. There is a clear deviation of the data from the models in all four filters.

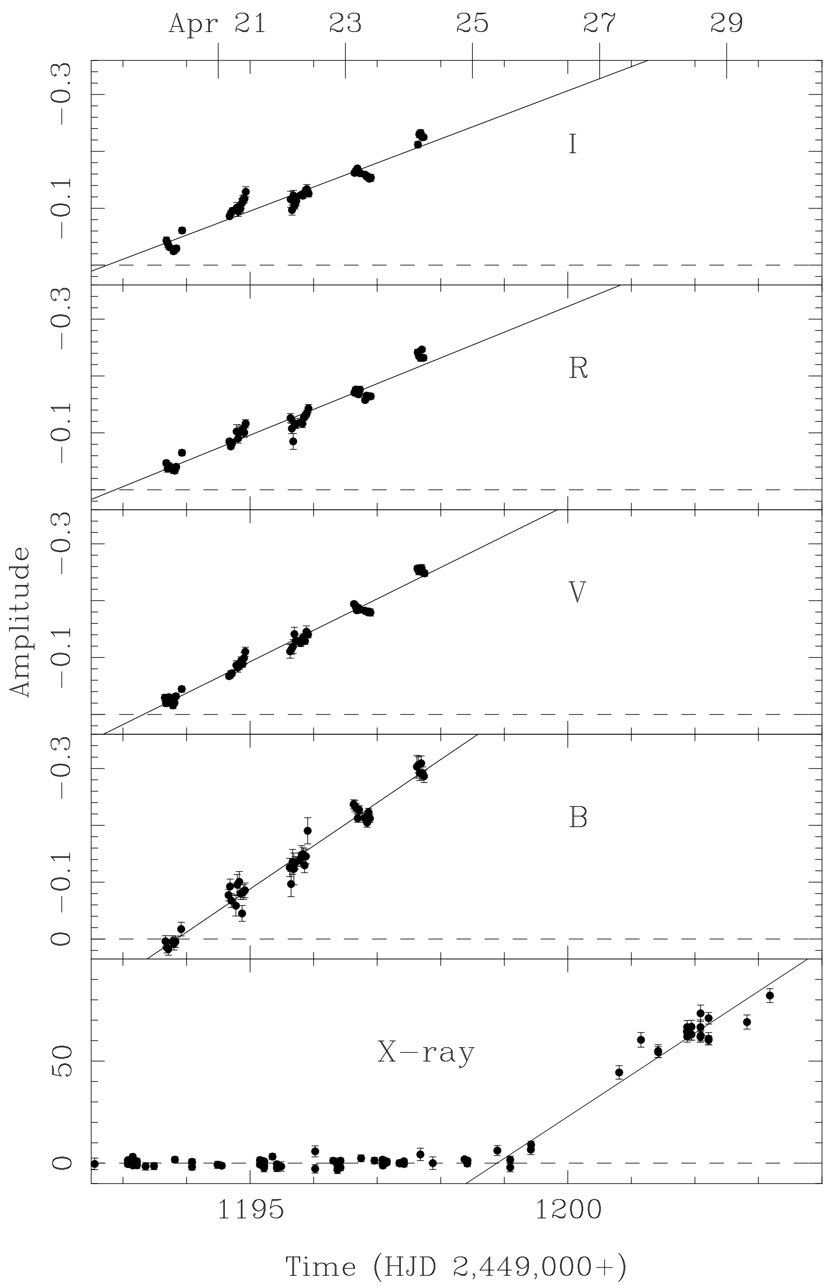

Fig. 2.— The residuals in the sense of the April photometry data *minus* the March models (in magnitudes) and the best-fitting lines are shown in the upper 4 panels. The bottom panel shows the X-ray intensity in counts per second (2 to 12 keV) as a function of time and the best fitting straight line to the 23 points between April 25.5 and 29.5. The measurements from the individual dwells and their uncertainties are shown (see Levine et al. 1996). The intensity of the Crab Nebula is about 75 counts per second. See Table 1 for the linear fit parameters.

2 and Table 1 shows some interesting trends. First, the rate of the brightness increase is the largest in B (0.0759 ± 0.0020 mag/day) and the smallest in I (0.0423 ± 0.0019 mag/day). However, the fitted time of the initial rise is the earliest in I (April 19.25 ± 0.29 UT) and the latest in B (April 20.34 ± 0.18 UT).

We took the 23 X-ray observations between HJD 2,450,199.09 and HJD 2,450,203.18 (roughly April 25.5 to 29.5, 1996) and fit a straight line to estimate the time of the initial X-ray rise. The results of the fit are shown in Table 1 and in Figure 2. The initial rise in the X-ray occurred April 25.38 ± 0.78, just over six days after the initial rise in the I filter (April 19.25 ± 0.29).

4. Discussion

The quiescent state of the black hole transients has been the subject of intense study. Recently, Narayan, McClintock, & Yi (1996, hereafter NMY96) presented their advection-dominated accretion flow (ADAF) model for the quiescent black hole binary systems. In the NMY96 model, there is an outer region of the disk at radii larger than several thousand Schwarzschild radii consisting of a thin disk and a zone interior to this where the accretion flow is a hot, optically-thin and quasi-spherical ADAF. In this ADAF region, the energy released by viscous dissipation is largely swept along with the flow and enters the black hole before it can be radiated. Consequently, the ADAF model is $\approx 100 - 1000$ times less efficient at producing X-rays than the standard disk model, a fact which can explain the quiescent spectra of A0620-00 and V404 Cyg (NMY96).

The two classes of models used to explain the cause of the outbursts of the dwarf novae (i.e. accreting white dwarf systems), the disk instability model (DIM; Cannizzo, Chen, & Livio 1995) and the mass-transfer instability model (MTI; Hameury, King, & Lasota, 1986, 1987, 1988, 1990), have in the past been applied to the soft X-ray transients. However, the MTI model as applied to the soft X-ray transients (especially those with periods less than about 9 hours) has recently fallen out of favor (Lasota 1996a,b; Tanaka & Shibazaki 1996). Also, the "standard" DIM, where the inner disk extends all the way down to the innermost stable orbit (about three times the Schwarzschild radius), has some difficulties when applied to the black hole X-ray transients (e.g. Lasota, Narayan, & Yi 1996; Lasota 1996a, 1996b; Tanaka & Shibazaki 1996). Therefore both "standard" theories need some modification when applied to the black hole X-ray transients.

Lasota, Narayan, & Yi (1996) developed a model for the outbursts in the black hole X-ray transients based on the NMY96 model. In particular, Lasota et al. (1996) show that the outburst mechanism in the X-ray transients must be associated with an instability in the cold outer disk of the NMY96 model (i.e. the advection dominated region cannot be responsible for the triggering of the outbursts). They go on to show that the instability could be a pure thermal accretion disk instability (moving either inside-out or outside-in) or an instability caused by enhanced mass transfer from the secondary where a small amount of additional matter causes a marginally stable disk to become unstable.

Our photometry results strongly suggest that the instability that created the April 1996 outburst started in the outer regions of the disk, and propagated inward (an "outside-in" event). The temperature profile of the accretion disk in the OB97 model is parameterized as $T(r) = T_{\rm disk}(r/r_{\rm disk})^{\xi}$. The best value of ξ was negative (-0.12 ± 0.01), indicating that the disk gets hotter as one moves inward. As a result, the inner regions of the disk are bluer than the outer regions of the disk. From Figure 2 and Table 1 we see that the optical brightening started first in the I filter and last in the B filter. Since the optical brightening in GRO J1655-40 appears first in the I band, the only region where this would appear as a "warm" zone is in the outer disk. Thus, it is reasonable to conclude that the disturbance in the accretion disk that gave rise to the increase in the optical flux was indeed an outside-in event.

Since either inside-out or outside-in transition waves are allowed in the Lasota et al. (1996) model, our demonstration that an outside-in event triggered the April 1996 outburst does not seem to constrain this outburst model. Paradoxically, our observation of the optical outburst might actually provide evidence for the presence of the ADAF region in the NMY96 model of the quiescent system. Consider the ≈ 6 day delay between the onset of the optical brightening and the brightening in the X-rays. This is analogous to the situation in certain dwarf novae systems where the rise in the optical flux precedes the rise in the UV flux by roughly one day (see Meyer & Meyer-Hofmeister 1994). In the standard DIM the transition wave should travel from the optical-emitting outer

edge of the disk to the UV-emitting inner edge of the disk in only a few hours. Meyer & Meyer-Hofmeister (1994) suggested that a "hole" in the inner disk could explain the observed optical-UV lag since the hole would take time to fill up before the hot UV-emitting region can be established (see Cannizzo 1993 for other possible solutions). In the case of GRO J1655-40, the ADAF region of the NMY96 model would act as the hole in the middle of the disk since the standard thin disk is truncated at the edge of the ADAF region. The fact that GRO J1655-40 is a much larger system than a typical dwarf nova (i.e. the orbital separation of GRO J1655-40 is $a = 16.77 \pm 0.19\, R_\odot$ [OB97] compared to a separation of $a = 3.29 \pm 0.29\, R_\odot$ for SS Cyg [derived from parameters given in Hessman et al. 1984]) explains why the the optical–X-ray lag in GRO J1655-40 is longer than the optical-UV lag in the dwarf novae. Detailed computations would be required to see if the ≈ 6 day delay between the optical and X-ray can be explained by the NMY96 model—such computations are well beyond the scope of this paper.

5. Summary

It appears that GRO J1655-40 was in a true quiescent state before the April 1996 outburst because of the low X-ray flux observed in March 1996 and the nature of the optical light curves from February and March 1996. We observed an increase in the optical flux about six days before the start of the X-ray outburst (which started near April 25.4). The character of the optical outburst depends on the color: the rate of increase was the fastest in B and the slowest in I whereas the brightening began first in I and last in B. The order in which the optical brightening started (from the redder colors to the bluer colors) suggests that the disturbance in the disk was an "outside-in" one. The substantial delay between the optical rise and the rise of the X-rays may provide indirect support for the ADAF model of the quiescent black hole binaries. Further detailed computations are needed to confirm this.

We are grateful to the staff of CTIO for the excellent support, in particular Srs. Maurico Navarrete, Edgardo Cosgrove, Maurico Fernandez, & Luis Gonzalez. We thank Jean-Pierre Lasota for the comments on an earlier draft of this paper. Partial financial support for this work was provided by the National Science Foundation through a National Young Investigator grant to C. Bailyn and by the Smithsonian Institution Scholarly Studies Program to J. McClintock.

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